

**Implications for understanding the Loch Lomond Stadial
glaciolacustrine varve sedimentation trends: a new varve thickness
record from Allt Bhraic Achaidh Fan, middle Glen Roy, Lochaber**

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Abstract:

Glen Roy, Lochaber is a key UK site for understanding Late Devensian environmental change, as it contains an annually-resolved glaciolacustrine varve record. This paper develops our understanding of varve sedimentation within Glen Roy through the examination of a new varve sequence located in a more proximal position on the Allt Bhraic Achaidh Fan, one of a series of major fans within the valley. This new varve record consists of c. 203 annual layers, much fewer years than at other sites in the Lochaber areas probably due to five significant hiatuses within the record. Varve sediment characteristics and thickness are comparable to, but not statistically correlated with, other varve series that were used to construct a consolidated varve record for the area, the Lochaber Master Varve Chronology. Sedimentological characteristics, analysed by thin section micromorphology, suggest that varve thickness changes within the basin are controlled mainly by distance from the valley sides rather than the position of the ice margin during the Loch Lomond Readvance, as previously proposed.

1.1 Introduction:

Annually-laminated sediments (varves) are key archives of Late Quaternary environmental change that are deposited and preserved in a number of different sedimentary environments (e.g. Zolitschka et al., 2015; Hughen et al., 2000; Peglar et al., 1984, Haltia-Hovi et al., 2007; Martin-Puertas et al., 2012). Whilst varves are being formed at the present time, much research has focused on varves that accumulated in former lakes, in particular 'palaeovarves' in glaciolacustrine contexts (e.g.; De Geer, 1912; Antevs, 1922; Caldenius, 1932; Ridge et al., 2012). Glaciolacustrine varves are

invaluable as they preserve a proxy record of environmental change during cold periods when biological productivity was suppressed (Ringberg and Erlström, 1999; Cockburn and Lamoureux, 2007; Menounos and Clague, 2008; Palmer et al., 2010) and the range of proxies available is restricted. In such circumstances, glaciolacustrine varve thickness is used to infer former environmental conditions. Varve thickness is controlled by sediment flux to the lake during the summer melt season (Ashley, 1975; Ringberg and Erlström, 1999; Ridge et al., 2012) and by limnological factors affecting the transportation of this sediment during the year. Varve thickness can reflect factors such as fluctuations in sediment supply driven by climatic variations (Rittenour et al., 2000; Hodder et al., 2007; Palmer et al., 2012; Heideman et al., 2015), the relative proximity of the point of deposition to the source of sediment influx to the basin (Smith and Ashley, 1985), and the extent to which the catchment is inundated by glacial ice (Leonard, 1986, 1997; Ridge et al., 2012).

In the UK, recent analysis of glaciolacustrine varves have been used to reconstruct glacier dynamics at locations that either record the retreat of the last British Ice Sheet or the advance and decay of the Loch Lomond Readvance (LLR) ice in Scotland (Palmer et al., 2008; Palmer et al., 2010; MacLeod et al., 2011; MacLeod et al., 2015). These reconstructions are based on microscale analysis of varves deposited in distal (to the ice front) positions of the lake basin. Distal varve deposits are advantageous for constructing chronologies of glacial extent because they are less susceptible to processes or events that disrupt the annual cycle of sedimentation, such as one-off, surge-type deposits, which are more prevalent in proximal locations. Consequently, distal locations are more likely to preserve longer continuous records. Nonetheless, studying distal sediments in isolation does not permit the reconstruction of basin-wide sedimentation patterns and thus a full understanding of the controlling factors on sedimentation (Ashley, 1975; Smith and Ashley, 1985).

The first reconstructions of the Lochaber lake systems in Scotland (Palmer et al., 2010) based on analysis of distal glaciolacustrine varves provided

information on the duration of the lake system in Glen Roy and the likely rate of shoreline development. However, the ice distal position of those varve deposits may not fully reflect patterns of sediment delivery to the glaciolacustrine basin. This paper reports on a new site, Allt Bhreac Achaidh (ABA; Figure 1) that is situated in a more proximal position with respect to the Loch Lomond Readvance glacier maximum in Glen Roy. The sedimentology of this new laminated sequence is compared to the previously reported distal sites of the Glen Turret Fan (GTF), Burn of Agie (BOA) and Loch Laggan East (LLE), which currently underpin the Lochaber Master Varve Chronology, (LMVC: Palmer et al., 2010). Finally, the data from ABA are assessed in terms of implications for sedimentary processes during the development of lake systems in Glen Roy.

1.2 Site Context:

Glen Roy is located approximately 15 km to the north east of Fort William and is a north bank tributary of the River Spean (Figure 1a). The Glen Roy and Glen Spean lacustrine systems were formed during the LLR when an ice dam prevented fluvial drainage to the west. The 260 m lake initially formed due to ice advance into the mouth of Glen Spean and subsequent ice advance into Glen Roy allowed the formation of the 325 m and 350 m lake levels in this valley, the lake levels controlled by the altitudes of the lowest available cols. On retreat, the lake waters were lowered sequentially in Glen Roy as lower cols became ice-free. Thus the position of the ice margin is directly linked to the down-valley limits of the prominent shorelines in the Spean and Roy valleys. More detailed information on this sequence of events is provided in Sissons (1979b, this volume) and Sissons and Cornish (1982b).

Allt Bhreac Achaidh Fan (ABAF) lies in the middle of Glen Roy at (OSGB: NN30146 88438) approximately 1 km to the north of the col separating Glen Roy and Caol Lairig (Figure 1c). It also lies 2 km to the north of a substantial accumulation of glacial deposits around the 'Viewpoint', which delimits the approximate maximum position of LLR ice in Glen Roy, and the down valley limit of the 350 m lake. ABAF has its apex on the western flank of Glen Roy at an altitude of 260 m with the adjacent relief rising to over 650 m in the upper

part of the catchment. The relatively small catchment of both the Allt Bhreac Achaidh (ABA) and the adjacent Coire an t-Seilich (Figure 2) is occupied by a small river, which incises the fan. The fan surface decreases to a height of 175m toward the River Roy where the fan is eroded and forms steep cliffs 10 m high (Figure 2). A delta, formed at 260 m, caps the fan (Figure 2). In addition there is an elongate ridge, positioned on the southern flank of the fan that has been interpreted as an end moraine associated with ice retreating toward the south during the Dimlington Stadial, when ice last inundated the whole valley (Peacock and Cornish, 1989).

The most recent descriptions of the sedimentology and geomorphology of ABAF were undertaken at seven sites across the fan surface and on the eastern flanks of the valley (Peacock and Cornish, 1989). There are relatively few sediment exposures within ABAF, the best being where the fan is incised. Here, it exposes coarse-grained sediments, where sand and gravel were interpreted to be deposited sub-aerially in peak fluvial discharge, then overlain by fine-grained, glaciolacustrine sediments (Peacock and Cornish, 1989; Figure 2). These glaciolacustrine sediments are intermittently observed in road sections on the distal edge of the fan; one such section is exposed on the northern flank of ABAF (OSGB: NN 30146 88438). Here, at a surface altitude of 198 m, Peacock and Cornish (1989) reported sediments composed of laminated grey clay (50 cm thick) overlain by 150 cm thick laminated brown silt with pockets of gravel, succeeded by 20 cm of a sandy-silty diamicton. Peacock and Cornish (1989) suggest that this sequence has not been affected by contortions, as observed at other sites across the fan surface. Miller (1987) ascribed these sediments to two units: an upper 'Group 1' composed of brown silt, and a lower 'Group 2', composed of grey silt and clay. At that time microscale sedimentology was not routinely undertaken and therefore the 'varves' identified by Miller (1987) at this locality were considered worthy of closer examination.

The ABA site occupies a useful position for providing new insights into the character of sedimentation in the glacial lakes of Glen Roy. The site is similar to GTF and BOA in that the deposits are positioned stratigraphically on the

fan surface and represent the last period of prolonged sedimentation on the fan surfaces. Consequently, the laminated sediments are likely to have been deposited during the same time period as the GTF and BOA varved sediments. Furthermore the site lies only 2 km from the maximum position of the LLR in Glen Roy; a more ice proximal locality with sediment predominantly sourced from the glacier that will have different sediment characteristics to those of GTF and BOA. Therefore, it will provide, for the first time, a more complete picture of the pattern of sedimentation in the former glacial lake and potential insights into sediment sources and transport paths and depositional mechanisms.

The main thrust of this paper is a detailed macro- and microscale description of the glaciolacustrine deposits preserved at ABA, and the generation of a glaciolacustrine varve thickness record. Possible implications of this new site chronology with respect to the Palmer et al. (2010) model for the duration of glacial lakes in Glen Roy are discussed

2.0 Methods:

Core samples were recovered from the ABA fan surface using an Eijkelpamp Stitz corer (50 mm diameter) with a Cobra TT percussion engine. This strategy was adopted to avoid sampling sediment exposures, which are subject to extensive slumping. Samples were described using standard lithological terminology at the macro- and microscale. Samples were prepared for thin sections using the methodology of Palmer et al (2008b). Thin-section slides were examined using an Olympus BH2 petrological microscope and an Olympus Stereozoom petrological microscope SZ60. Image analysis was conducted using images captured with a Penguin Pixera 600es camera and analysed with Image Pro-Express 4.5 software and standard software packages.

3.0 Results:

3.1 Introduction:

The lithostratigraphy presented in this paper is described from a single core extracted from location A on the fan surface (Figure 2). This core, although

interrupted by a number of hiatuses, provides the most complete record from this part of the ABA.

3.2 Macroscale description of ABA:

The lithostratigraphy of the core is presented in Figure 2 and consists of four units. Unit 1, at the base of the sequence (187.27 – 187.35 m OD), is composed of sandy gravel. Unit 2 is rhythmically laminated fine sand and coarse silt between 187.35 – 187.38 m OD. Unit 3 (187.38 – 188.47 m OD) is subdivided into 3 sub-units. Unit 3a is composed of finely laminated clays, with very fine couplets of silt and clay occurring between 187.38 – 187.79 m OD. Unit 3b is observed as thicker couplets of very thin silt laminae and thicker laminae of clay occurring between 187.79 – 188.47 m OD. Within Unit 3b, there are five distinct beds/ thick laminae characterised either as a diamicton with anomalously large clasts, possibly as dropstones (B1: 187.69 – 187.73 m OD; B2 187.79 – 187.89 m OD; B4: 188.03 – 188.07;), or deformed laminations (B3; 187.95 – 188.01 m OD; and B5; 188.29 – 188.35 m OD). Unit 4 is a massive silty clay between 188.47 – 189.47 m OD.

The total thickness of fine-grained sediments at ABA with laminated couplets of silt and clay is 1.12m, which is comparable to the records extracted from GTF. By comparison to GTF and LLE, this section of laminated sediments at ABA has more observed macroscale hiatuses but, critically, also has thin couplets of silt and clay at the base, which is overlain by thicker couplets of silt and clay. On this basis the laminated sections (Units 2 and 3) of the core was examined using the thin section micromorphology, described below.

3.3 Microscale description of laminated sediments in ABA:

In this section the microfacies of the rhythmically laminated sediments identified at the microscale in Units 2 and 3 are described. Unit 2, observed between 187.35 – 187.38 m OD, are normally graded from very fine sand to medium silt (Figure 3A) and range between 1-3mm in thickness. There is no obvious clay component to the lamination texture unlike the distinct clay layers described below in Unit 3. The distinct sediment characteristics of Unit 3a and 3b occurring between 187.38 – 188.47 m OD demonstrate regular

alternations between coarse (fine sand to medium silt) grain sizes and fine (very fine silt and clay) fractions (Figure 3B-3D). There are sharp contacts between the coarse and fine laminations and from the fine to coarse laminations. The silt component is either massive, normally graded or inversely graded and, in certain examples, can be composed of multiple very fine laminations, which are more common in Unit 3b (Figure 3D). However in Unit 3a the coarse layer is composed of either a single lamination of well or moderately sorted very fine sand or coarse silt (Figure 3B) or occasionally is composed of poorly sorted fine sand and very fine sand in a matrix of medium silt (Figure 3C). The majority of lamination types that form the coarse layer in Units 3a and 3b have been observed previously in GTF, BOA and LLE, however it is noted here that, at ABA, there is a higher proportion of laminations that possess poorly-sorted laminations in the coarse component (Figure 3C). The fine layers in both Unit 3a and Unit 3b are typically composed of very fine silt normally grading into clay, which, under cross-polarised light, display a masepic fabric.

Anomalously large grains are common (Figure 3E; 3H) within the laminated sequence as a whole and fall into two categories: the first are grains and clasts that cause penetration and bending of the laminations at the bottom contact allied to bending and on-lap of the upper contact. These dropstones are fine (normally with a-axis of 1-4 mm) and do not break the sedimentation of the laminations. However there is evidence of rucking at the bottom contact and rupture at the bottom and top contact (Thomas and Connell, 1985) in places and which are associated with the beds that interrupt the sedimentation in Units 3a and 3b. In these cases the anomalously large grains are also associated with unsorted sands silts and clay, forming thin diamicton beds as noted above (B1, B2, B3; Figure 4). Also within Unit 3b there are zones of deformed laminations noted at the macroscale. The depths of these beds are highlighted in Figure 4.

3. Interpretation of the Macro- and Microscale Sediment Facies.

The macro and microscale sediment facies preserved at ABA mainly provide evidence for glaciolacustrine sedimentation on the fan surface. Unit 1

probably represents the original fan surface with the presence of sands and gravels and passes into Unit 2 containing normally graded silt and sand laminations. These laminations represent pulses of sediment delivered to the lake basin probably by underflow in high sediment concentrations (Johnsen and Brennand, 2006). The coarser nature of these graded laminations and the lack of clay in these deposits at the base of the sequence indicate that limnological conditions did not support varve sedimentation at the very start of the lake's development.

Units 3a and 3b are characterized by regular alternations of layers of silt with sharp contacts to succeeding clay layers. These in turn have sharp contacts to succeeding silt layers. The silt layers do not grade upwards in grain size and can show evidence of multiple pulses of sediment being inputted into the basin. The clay layers are well sorted with grain size grading from base from very fine silt to clay. These structures are comparable to features observed at the macroscale by, for example, De Geer (1912) and Antevs (1922), with further detail provided by Ashley (1975), Smith (1978), Smith and Ashley (1985) and Ridge et al. (2012) at the macroscale. Similar structures have also been described at the microscale by, for example, Ringberg and Erlström, (1999) and Palmer et al. (2008a, 2010). In both cases this leads to the interpretation of the structures as glaciolacustrine varves. The sediment is delivered either by underflow or overflow to the lake basin during the melt season and sedimentation of the coarse component is initiated almost instantly after the flow waned. Thus the melt (summer) season is represented by the coarser component of the laminations. The onset of lake water freezing at the end of the melt season inhibits the formation of surface currents, and permits the deposition of the finer clay fraction from suspension in the water column. Although there is a sudden change to this style of sedimentation, there is some very fine silt still present in the water column and this is deposited first before the further accumulation of clay. There is a sharp contact between the clay and succeeding sand/silt layer representing the sudden onset of sedimentation during the melt season. In certain cases there are multiple pulses of sediment to the basin during the melt season represented by the very fine lamination in the coarser silt.

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274 Within the sequence, it is important to note that there are breaks in the
275 annually-laminated sediments that reflect different mechanisms within the
276 glaciolacustrine system. Firstly, the presence of dropstones and drop-grains
277 with anomalous grain size of the grains allied to the penetration, rucking and
278 onlap of the laminated structures suggest suspension settling of the grains
279 through the water column and disruption of the underlying sediment (Thomas
280 and Connell, 1985). These are randomly distributed in the varve sediments,
281 but also the amount of sediment delivered by this mechanism varies:
282 sometimes there are isolated grains or sufficient material to form discrete thick
283 laminations and thin beds of 4 cm and 10cm thickness (e.g. B1 and B2 in the
284 sequence). The larger grains in Bed 1 and 2 are associated with unsorted
285 finer material and could either represent deposition from an iceberg, or a
286 subaqueous slump from the valley side, which may have been seismically-
287 induced (Ringrose, 1989). However due to the restricted sample size of the
288 core it is difficult to ascertain the lateral continuity of these beds and hence to
289 clarify their likely origin. Beds 3 and 5 within the laminated sequence are
290 represented by deformed laminations which are folded or contorted and
291 caused by the slumping or displacement over short distances of previously
292 deposited glaciolacustrine varve sediment.

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294 Unit 4 is massive silty clay with no obvious laminated structure at the
295 macroscale, probably representing further fine-grained glaciolacustrine
296 sedimentation, which may have been laminated initially but, possibly due to
297 local mass movements and soil forming processes, the original laminated
298 structure has been disrupted. As such, all that can be concluded is that further
299 fine-grained sediments were deposited, but no additional information on the
300 varve thickness records can be provided.

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302 In summary, the sedimentological evidence from ABA indicates that the
303 glaciolacustrine system begins with the development of non-annual rhythmic
304 sedimentation of silt and sand deposited on the ABA fan surface. This is
305 succeeded by 1.08m of predominantly glaciolacustrine varve sedimentation,
306 which is commonly interspersed with single events such as ice-rafted debris,

diamict deposition and deformation events. This causes the varve sedimentation record to be discontinuous although the existence and character of the varved sequence deserves further comment.

3.5 Description of Varve Thickness Record

A varve thickness diagram for the sequence of varves preserved at ABA (ABASC14; Figure 4) has been generated. This consists of 203 years of sedimentation, but can be divided into three sections on the basis of the varve thickness: lower, middle and upper (Table 1). The lower section is composed of 111 years of sedimentation characterised by similar summer:winter thicknesses and dominated by a single (undivided) summer lamination. The mean thickness is 1.71mm for all of the varves in this section, although there are 26 anomalously thick varves (>2.5mm thick) interspersed throughout this section. The middle section of the ABASC series comprises 76 years of sedimentation (varve years 112-188 years, characterised by winter layers twice as thick as melt season layers, with evidence for microlamination within the melt season layers. Mean thickness is 4.98mm and appears to be less affected by one-off extreme years of sedimentation than the lower section. The upper section of ABASC is defined by varves 189 to 203, implying a duration of 14 years. The winter layers in these are normally at least double the thickness of the melt season layer and there are multiple microlaminations in the melt season components. The error on the overall estimate of 203 years of varve sedimentation was assessed by comparing two independent counts on the same sequence by two operators. The error is relatively high at 8%, mainly due to complications encountered in Bed 1-5 within the sequence, and interference caused by dropstones and drop-grains.

There are key similarities between the varve thickness record and structures observed in the ABA record when compared with the GTF and LLE records (Figure 4). Firstly, the ABA record is characterised by thinner varves at the base of the sequence, which are overlain by thicker varves in the middle section, which in turn are succeeded in the upper section, by a package of the thickest varves in the whole sequence. In each of these sections, the average thickness of the varves is marginally greater at ABA than in equivalent

sections at GTF, LLE and BOA. In addition, a transition between the lower and middle sections of gradually increasing varve thickness (varves 93-110) is also clearly observed at GTF (Figure 4).

Secondly the relative thickness proportions between winter and summer melt season layers varies from essentially equal in proportion in the lower section to at least a 2:1 ratio in the succeeding section. Finally, there is a correspondence with GTF and LLE to ABA in the presence of mainly single layers in the summer melt season deposit for the lower section, whereas the summer melt season layers in the middle and upper sections have multiple microlaminations. It should also be noted that the duration of the ABASC14 is a minimum of 203 years, significantly less than that reported for GTF (276 years) or for LLE (490 years). The significance of these observations is discussed in section 4.

There are, however, some notable discrepancies between the ABASC record and the GTF and LLE records, besides the differences in varve counts. This is most evident in the lower section of ABASC, which shows a higher frequency of anomalously thick varves (Table 1). The thickness of these thicker varves is greater than 3 mm and these tend to mask the overall trend observed within the ABASC sequences. When these thicker varves are removed from the calculation of mean thickness for the lower section, there is little difference between the mean varve thickness of ABA (1.59 mm) and GTF (1.45 mm). Attempts to correlate statistically the different sections proved difficult due to the nature of the varve thickness records at ABA. The relatively short middle and upper sections segments of the varve thickness record are disrupted by the beds 1-5 of deformed lamination and diamicton beds and therefore too short to permit correlation. The lower section of ABA, years 1-111, does correlate significantly to the lower section of GTF when including the thicker (>3 mm) varves ($r = 0.465$; $n=111$, $p<0.01$). This correlation matches year 1 of the ABA varve thickness record to year 6 of the GTF record and year 111 at ABA to year 116 of the GTF record (Figure 4). Despite the difficulties encountered with other parts of the ABA record, the statistical match achieved for the lower section, allied to similarities in sedimentological characteristics

(varve thickness trends, relative proportions of winter to summer layers, the number of events recorded in the summer layers), collectively provides good evidence that the ABA record matches those of GTF and LLE.

4.0 Discussion

4.1 Understanding the distribution of fine-grained sediment in Glen Roy.

The interpretation of these glaciolacustrine varves in middle Glen Roy is important for understanding the sequence of events in Glen Roy. In theory, varves deposited closer to an ice margin should have thicker annual layers of sedimentation than those deposited more distally (Eyles and Miall, 1984; Smith and Ashley, 1985; Ringberg and Erlström, 1999). The sites of GTF, BOA and LLE, at 8, 10 and 18 km respectively from the maximum position of the Roy LLR ice front, are distal to the ice margin, which is indicated by the average thickness measurements for the varves (~0.5 mm to ~ 5.5 mm; Table 1). The varve thicknesses represented in the ABASC sequence range between ~1.0 mm to ~7.0 mm, which are also typical of distal glaciolacustrine varves (Smith and Ashley, 1985, Smith, 1978; Palmer et al., 2010). However the more ice proximal position of ABA might have been expected to produce thicker varve deposits, a product of melt season layers containing multiple silt or fine sand laminations with evidence of current structures (e.g. Ridge et al., 2012), yet varves of this type are not common within the sequence. Furthermore, the sedimentary structures in the lower section of ABA, GTF and LLE are similar, commonly consisting of single-layer summer laminations. As the varves become younger, they are characterised by multiple pulses of sediment in the summer melt season and there appears to be coherence in the style of sedimentation at comparable points of the varve thickness records in Glen Roy and Glen Spean. Given these strong similarities between varve records that are both proximal and distal to the LLR ice front, it can be concluded that varve thickness does not appear to be controlled by the position of the ice margin, within the Glen Roy lake system.

An alternative explanation for these basin-wide patterns is that sediment supply was sourced from tributary catchments, in accordance with the model proposed by Ashley (1975) for Glacial Lake Hitchcock in New England, USA.

In the Glen Roy case, streams and rivers from small valleys such as the Canal Burn, Burn of Agie, East Allt Dearg, Allt Na Reinich, Brunachan and Allt Bhreac Achaidh, could have delivered high sediment loads into the lake basin to form either subaqueous fans or deltas that accumulated on the lake floor or close to the corresponding shoreline. Sediment probably started to accumulate as subaerial fans after ice retreat at the end of the Dimlington Stadial (c.f. Peacock, 1986) with perhaps further deposition of coarse clastic material on the fan surface during the Loch Lomond Stadial. However the subsequent colder climates associated with the LLS would have reactivated coarse sediment loads to the fan/deltas with coarser sediment loads being deposited in deltas close to the lake margins when streams entered the body of standing water, allowing the fine suspended sediment to be transported across the fan/delta surface and deposited at distal localities. As such the proximal to distal varve thickness relationships are represented by thicker varves at the lake margins and thinner varves forming towards the centre of the valley floor, at the distal margin of the fan surface.

Whilst the tributaries are considered to be the dominant source of sediment supply to the basin, in the case of the ABA fan varve sequence, it is likely that material from the ice margin at the Viewpoint was also contributing some sediment in the form of IRD (ice-rafted debris) from the calving glacier margin or from extreme high sediment discharge events (the anomalously thick varves in the lower section), which delivered a greater concentration of sediment that penetrated further into the lake basin. Whilst dropstones and grains are also present in the GTF, BOA and LLE sequences, they do not tend to be associated with laminations and beds of diamicton as observed at ABA. Alternatively the diamicton beds could also reflect deposition from either higher discharge events flowing across the fan surface and sourced from adjacent catchments, or from subaerial and subaqueous slumps on the valley sides, possibly seismically- induced. As mentioned in Section 3, however, in the absence of more sections from which to establish the lateral continuity of the units, it is presently difficult to test these hypotheses.

Varve thickness could also reflect changes in lake level, which would change the distance between the point of deposition and the point of sediment ingress; decreased water levels reducing and higher water levels increasing the distance..Whilst water levels fluctuated on several occasions in Glen Roy (Jamieson, 1863; Sissons 1978), the lake in Glen Spean remained at 260 m throughout the entire period during which the lake system existed. Since the record at LLE in the Spean system reveals the same pattern of thin varves overlain by thick varves as is observed at GTF and ABA in the Roy system, it is unlikely that fluctuations in water level controlled the longer-term trend observed in varve thickness. Since the water level in Glen Roy is controlled by the position of the ice margin, the longer-term (decadal and centennial scale) trends in the varve thickness record are not likely to reflect advance and retreat of the LLR glacier into lower Glen Spean and Glen Roy, or was overridden by more important forcing agents, such as regional temperature and/or precipitation changes.

Distal glaciolacustrine sedimentation in the Glen Roy system does not appear to have been driven by distance from the ice front, as previously assumed by Palmer et al. (2010). Instead, sediment in Glen Roy was being sourced and supplied from small tributary catchments such as East Allt Dearg, Coire an t Seilich, Allt Na Reinich and Brunachan, through paraglacial resedimentation of glacial sediments deposited during the latter stages of the Dimlington Stadial. The lower part of these catchments on the floor of Glen Roy was thought to be the focus of sediment accumulation deposited either subaerially or subaqueously during the final phases of the last deglaciation (Peacock, 1986) with further sedimentation on the fan surface during the LLS. In proximal positions to the fan, the LLS sediments are composed of sand and gravels deposited when the flow velocity of streams decreased on entering the still lake waters (e.g. deltas at 260 m; Figure 2). On, for example, the Glen Turret Fan, East Allt Dearg Fan and Allt Bhreac Achaidh, sedimentation on the distal areas of the fan surface is dominated by fine-grained glaciolacustrine varves (Palmer et al., 2010), where 1-1.5m of sediment is commonly found on these fan surfaces, representing a maximum of ~270 years of sedimentation in Glen Roy. This would also have been true of the

LLE and BOA sequences where sedimentation rates during the LLS in distal positions of the fan surface were also comparably low. The sources of sediment supply to each of the fans were the small, restricted catchments immediately above the individual fans observed in middle and upper Glen Roy, rather than directly from the ice at the mouth of Glen Roy. It is therefore concluded that the data reflect a proximal-to-distal sedimentation pattern across the fan surfaces (Figure 5).

4.2 Implications for reconstructing events in Glen Roy and Glen Spean.

This finding has implications for previous interpretations of the Glen Roy and Glen Spean lake systems, based on the published site chronologies. Firstly, the Glen Roy system is potentially unique in being able to distinguish the duration of time that different lake levels were attained (Palmer et al., 2010) through the varve record. The duration of the lake systems lasted for a minimum of 515 years (Palmer et al., 2010), although there is evidence, such as the rhythmic sedimentation of sands and silts at the base of the ABA sequence, that suggest the glacial lakes existed for a longer period, but this is unquantifiable. However, it is probably not possible to distinguish the duration of time that the lake levels were maintained at the 260 m, 325 m and 350 m levels in Glen Roy because varve thicknesses do not reflect the position of the ice margin while none of the changes in varve thickness are explainable by lake level changes.

If the lake duration is in the order of 515 years, the observations of the shorelines being eroded quickly (Sissons, 1978) still remains valid. The overall duration of the lake system is 515 years and is unrevised by the new ABASC. If an equal period of time were attributed to each of the five successive lake level events, which allow sedimentation in Glen Roy (260 m, 325 m and 350 m lakes in the rising limb with 325 m and 260 m lakes in the falling limb) and Spean lakes, the duration of each lake system would be approximately 103 years. In this scenario, the 260 m and 325 m shorelines would have approximately double the amount of time for shoreline erosion as the 350 m shoreline. The fact that there is little difference in width between the 260/325 m lake shorelines on the one hand, and the 350m lake shoreline on

the other, implies that the shorelines were eroded to their maximum widths within ~100 years. It might therefore be argued that shoreline thickness was controlled mainly by the competence of the bedrock which, in turn, may have been determined by periglacial action on exposed bedrock prior to the formation of the lake systems during the LLR, or alternatively the result of dilation of the bedrock after retreat of the Late Devensian Ice Sheet. Whatever the cause, only the outer ~10 m of the local bedrock appears to have been susceptible to excavation of shore platforms during the LLR.

A second significant implication of these new data is that if varve thickness is not controlled by either the position of the ice margin or by changes in water depth, then it is most likely that it was regional climatic factors that controlled sediment supply to the lake basin. Whilst Ridge et al. (2012) consider that the intensity of the melt season on glacial ice, which is a product of summer temperature, can affect the thickness of varves, it has been demonstrated here that sediment sourced from the glacier had a limited effect on varve thickness variations in Glen Roy. From this study, the source of the material was derived from small catchments of the higher ground above the fan/delta deposits on the valley floors. An initial input of sediment to the lake would reflect the high discharge associated with melting of the winter snow pack in these catchments and further sediment would have been transported to the basin by heavy precipitation events during the summer (Tomkins and Lamoureux, 2007; Loso et al., 2010). This accords with the observations of Palmer et al. (2012), which suggest that a greater significance should be placed on the number of sediment layers (number of laminations) recorded in summer layers rather than on summer layer thickness. Fluctuations in the summer layers are attributed either to a series of temperature fluctuations that intermittently melt the remnant snow pack in the melt season releasing more sediment to the lake basin, or to the number of heavy precipitation events that occur during the melt season, or to a combination of both factors. Consequently, it is likely that the varve thickness variations in Glen Roy and Glen Spean were controlled by either precipitation or temperature.

Conclusions

- The ABA sediment sequence preserves a record of glaciolacustrine deposition with part of the sequence composed of varves. There are a series of hiatuses in the sequence in the form of ice-rafted debris, deformed laminae and massive beds of sand. The higher number of hiatuses when compared to other distal sites in Glen Roy and Spean reflects the closer proximity of the ABA site both to the valley sides and to the ice front maximum position.
- The varve thickness record obtained from ABA reveals a key characteristic, where thinner varves are deposited prior to deposition of thicker varves, a phenomenon that is common to other sequences in Glen Roy and Glen Spean.
- A site chronology of 203 varves for ABA has been constructed, which is less than the 270 varves recorded at GTF.
- The discovery of thin varves in middle Glen Roy with structures comparable to other sites in Glen Spean and Glen Roy suggests that the sediment sources are dominated by adjacent valley tributaries, rather than directly from the ice and that the varve thickness record might be controlled by either precipitation events in the summer or temperature.
- The new data do not alter the estimate of the overall duration of the glaciolacustrine system, which remains as 515 years, but the new interpretation of the controls on varve thickness variations invalidates the use of these data to infer the duration of individual lake levels.

Acknowledgements:

The authors gratefully acknowledge the Scottish Natural Heritage for their help in accessing the land within the National Nature Reserve and the role of Lochaber Geoparks for their continued support and interest in the ongoing research in Glen Roy and Glen Spean. Two anonymous reviewers are thanked for their very thoughtful reviews which have improved the manuscript.

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Figure 1: Location map of key landforms and locations of varve sequences in Lochaber. A) Outline of the Loch Lomond Readvance ice cap in Scotland and the location of the study area. B). Inset of the study area with a schematic of the Loch Lomond Readvance ice cap limits in the area of Glen Roy and Glen Spean (Sissons, 1978). C) Location of the Allt Bhreac Achaidh and its relationship to other varve sites in Glen Roy and Glen Spean and other fan deposits in Glen Roy.

Figure 2: Schematic geomorphological map of Allt Bhreac Achaidh Fan (after Peacock and Cornish, 1989), which describes the spatial relationships between the landforms and key sediment sequences referred to in the paper. Contours are derived from data supplied by Digimap. Sediment log describing the core sequence from location A on the ABAF. Four units are identified with a full description of the sediment units provided in the text.

Figure 3: Photomicrographs of the microfacies observed within the ABAF sequence. All images are taken under cross-polarised light and the scale differs according to each image. In images A – C, yellow bars represent the winter layer of the varve sediments and the green represents the summer layer of the varves.

A) Example of glaciolacustrine varve microfacies observed in Unit 3a of ABA. The summer melt season layer is a single laminae of well sorted coarse silt and the winter layer is very fine silt grading to clay with sharp upper and lower contacts.

B) Example of glaciolacustrine varve microfacies observed in Unit 3a of ABA. In the summer melt season highlighted there is an input of medium and coarse sand during the middle of the season.

C) Example of glaciolacustrine varve microfacies observed in Unit 3b of the ABA sequence. Here there are multiple laminations during the summer melt season comprised of alternations between coarse and medium silt, before the sharp contact to the winter layer.

D) Rhythmic non-varve sedimentation observed at the base of ABA sequence.

E) Example of a dropstone penetrating through annually-laminated sediments. These can form continuous thin beds within the ABA sequence that are hiatuses, but also isolated grains with subsequent sediments draped over the grains suggesting continuity of sedimentation. Also note that the coarser laminations are composed of unsorted sediments.

F) Example of silts and clay, probably deposited as glaciolacustrine varves, which have been subsequently been deformed. This is reflected in the contorted nature of the lamination structure and the relatively high birefringence fabric of the clay. These are present in Beds 3 and 5 that are observed within Unit 3b.

G) Example of predominantly diamictic material that is observed in Bed 2 and which still retains some evidence of laminated sediments that are now contorted. This deformation may have been caused by the slumping of material from the valley side local to the site on the fan.

H) Example of larger grains within unsorted sediments of summer laminations and the contorted winter layers associated with the deformed Beds 3 and 5.

Figure 4: Lithostratigraphy of the ABAF sequence (A), varve count and thickness record for the ABAF sequence (B) and proposed correlation to the GTF and LLE varve thickness record in Glen Roy and Spean (C). Dashed line between ABAF record and GTF represent the position of the start and finish varves for the statistically significant correlation of $r = 0.465$ for the varves observed in Unit 3A. The dotted lines between GTF and LLE highlight the position of the sand bed and deformed laminations in these sequences (Palmer et al., 2010) and tentative match of the top most bed in unit 3b from ABA to the deformed laminations is made with a question mark. It is important to note that there is a thickening of the varve thickness record in ABA between varves 80-120, which might correspond to the thickening observed in GTF and LLE around the deposition of the sand bed and sits at a comparable part of the ABA varve thickness record based on the correlation.

Figure 5: Schematic figure of theoretical sedimentation patterns that occur in Middle Glen Roy when the ice is at its maximum extent. This is based on the conceptual model produced by Ashley (1975) for Glacial Lake Hitchcock in

North America. Sediment is transported into the lake waters directly from the ice with progressively thinner varves developing with greater distance from the ice margin (P1 – D1). However the evidence presented in this paper would suggest that there is a proximal to distal thinning of varve thickness across fan surfaces (P2-D2) when sediment is transported to the basin via alluvial transport from small mountain catchments, as is the case at ABAF.

Table Captions:

Table 1: Comparison of the varve thickness characteristics of the ABA site to the GTF and LLE measurements for the different sections of the varve chronologies.

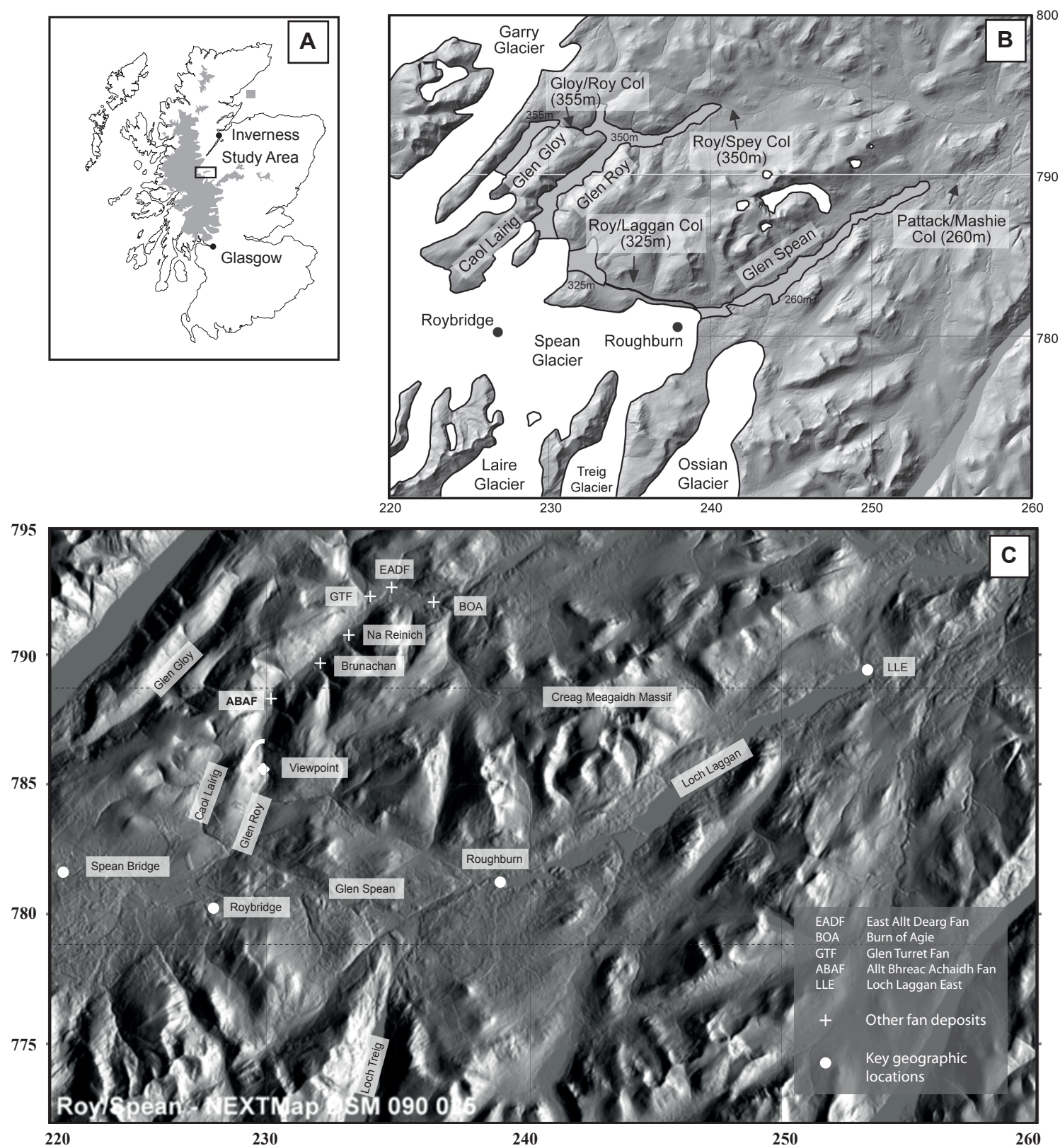
769 Table 1:

770

Section	Years	Ratio (W:S)	Mean Summer Thickness	Mean Winter Thickness	Mean Total Thickness	GTF	LLE
Upper	189- 203	2:1	1.18	6.244	7.03 (2.57)	5.11	5.48
Middle	112- 188	2:1	1.126	3.039	4.98 (2.69)	4.32	1.93
Lower	1-111	1:1	0.937	1.132	1.71 (0.96) 1.59 (0.63)	1.45	0.65

771

Figure 1



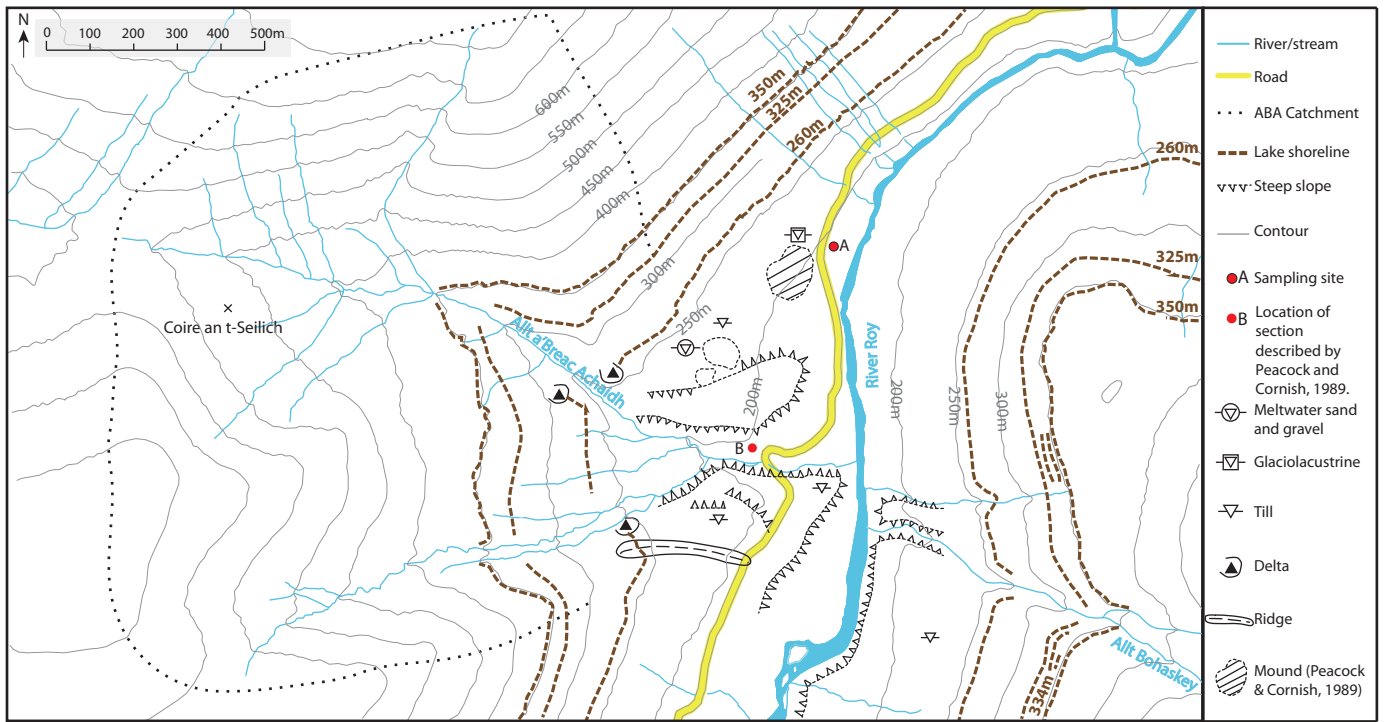


Figure 3

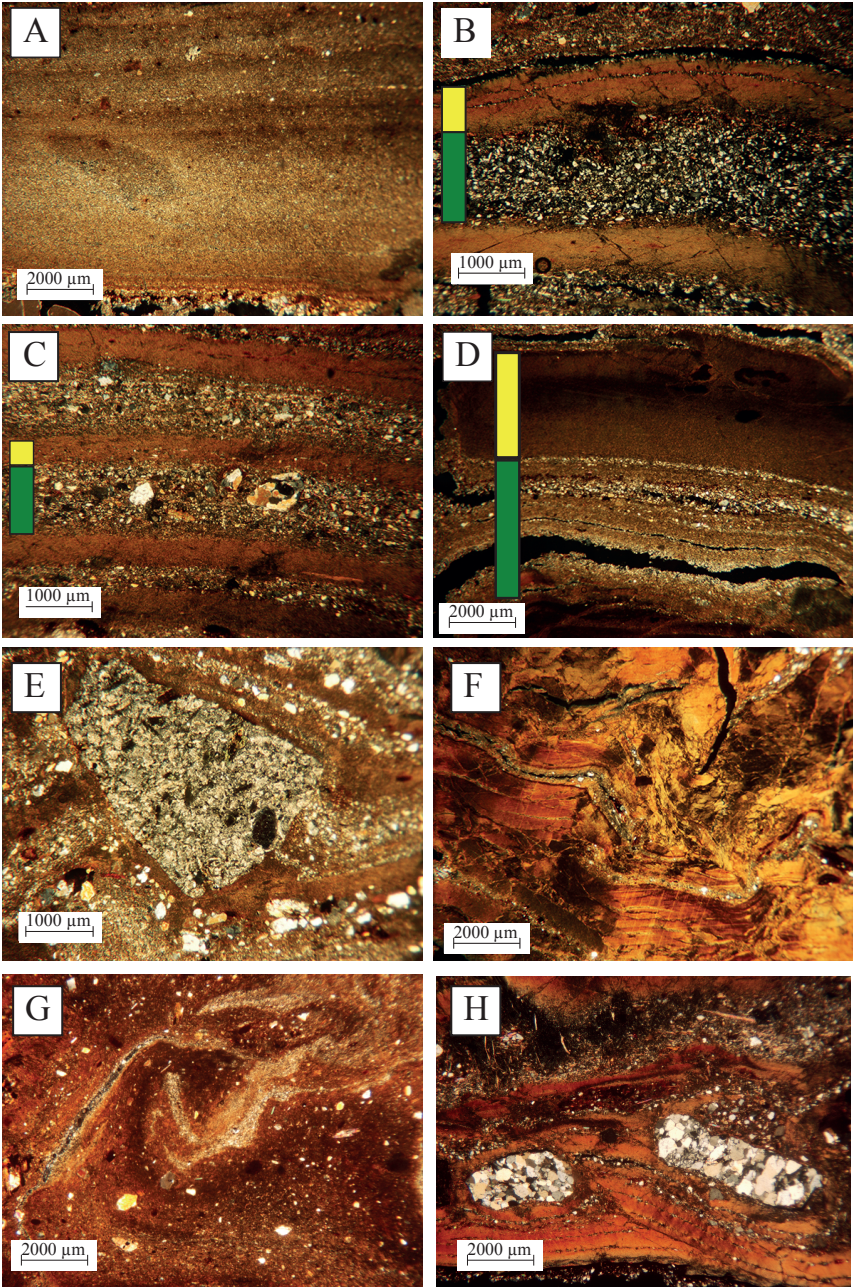


Figure 4

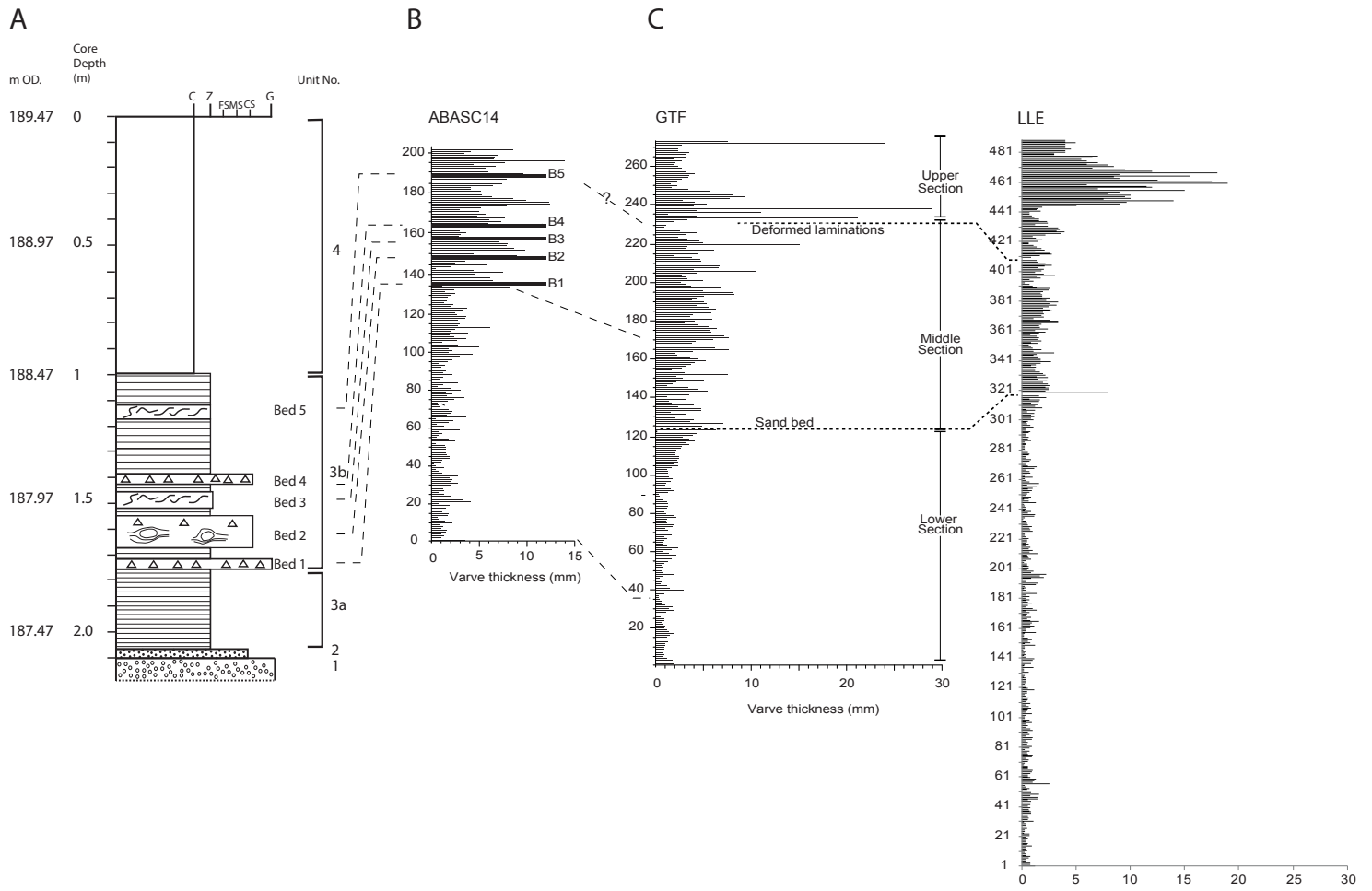


Figure 5

